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The rain effect on Aquarius' L-band sea surface brightness temperature and radar backscatter

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ABSTRACT

We analyze the surface emissivity and radar backscatter measured by the Aquarius L-band radiometer and scatterometer under rainy conditions. The residual signals due to rain are derived from measurements after accounting for roughness due to wind and flat surface emissivity. The wind roughness is accounted for by a geophysical model function (GMF) built using rain-free data. Using more than one year of Aquarius data collocated with SSMI/S, WindSAT rain rate and NCEP wind, our analysis reveals rain rate dependence in radar backscatter and surface emissivity, which become increasingly significant as the wind speed approaches zero and not significant above 15 m s^{-1}. The effect of rain on radar backscatter is dominated by raindrop splashing as indicated by the incidence angle dependence and polarization characteristics of the residuals.

1. Introduction

Ocean salinity is a key state variable linking global water cycle and ocean circulation. Variations in sea surface salinity (SSS) reveal the ocean's response to fresh water (FW) forcing resulting from combined effects of precipitation, evaporation, river runoff, and ice melt. The NASA Aquarius passive/active L-band microwave instruments on board the Satellite for Scientific Applications-D (SAC-D) operated by the Argentine Space Agency Comision Nacional de Actividades Espaciales (CONAE) is designed to provide spaceborne observation of SSS over the global ocean (Lagerloef, 2012; Lagerloef et al., 2008, 2012). Since the launch in August 2011, Aquarius data has shown interesting features, such as the salinity structure of tropical instability waves (Lee et al., 2012) and the upper ocean response to hurricane Katia (Grodsky et al., 2012). Validation on the recently released Aquarius version 2.0 data indicates achieved accuracy of 0.3 PSU globally, when averaged on a monthly time scale (Lagerloef et al., 2013), close to the mission requirement of 0.2 Practical Salinity Unit (PSU). Many efforts are still ongoing to further improve the retrieval algorithm, such as analysis of error dependence on regional and geophysical parameters. This study focuses on one of those parameters, the effect of rain.

Precipitation, as the dominant FW component at air–sea interface, complicates the remote sensing of SSS in various aspects. The measurement principle of Aquarius is based on the sensitivity of the L-band sea surface brightness temperatures (T_B) to SSS. With other effects held constant, higher T_B corresponds to lower SSS at given sea surface temperature (SST). Under rain, SSS is expected to decrease due to surface freshening, and we would expect to observe an increase in T_B. However, other factors also affect T_B under rain. While absorption at L-band by rain is small, rain will cause additional surface roughness and excess surface emissivity, which translates to higher T_B. We must account for this effect to obtain accurate SSS retrievals in rain. The challenge is to separate rain-induced roughness related T_B increase from those due to real SSS change. It is also unknown how long the freshwater accumulated from precipitation stays at the surface in the form of so-called freshwater lenses before it dissipates through the oceanic mixing process at various regions over global oceans (Henocq et al., 2010; Lukas & Lindstrom, 1991; Reverdin et al., 2012). As pointed out by Boutin et al. (2013) based on the comparison of SSS measured by the Soil Moisture and Ocean Salinity (SMOS) (Font et al., 2004) and ARGO (Array for Real-Time Geostrophic Oceanography) (Roemmich & the Argo Steering Team, 2009), the SMOS SSS negative bias in the tropical Pacific Ocean likely linked to the rain variability and the vertical salinity stratification.

To avoid the impact of rain, the Aquarius wind roughness GMF was built using L-band radiometer and radar measurements under rain-free conditions. Ancillary rain data, matchup with Aquarius measurements, were used to filter out data records with possible rain contamination. This approach ensures accurate modeling of excess emissivity from wind-induced roughness (Yueh, Tang, et al., in press). However, when this rain-free GMF is used to retrieve SSS in rain, we expect additional bias in SSS due to rain splash. The impact

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of raindrops on the water surface can significantly change its roughness, as demonstrated in numerous laboratory and aircraft measurements (e.g. Bliven et al., 1997; Braun & Gade, 2006; Jones et al., 1977; Lemaire et al., 2002; Moore et al., 1979; Sobieski et al., 1999), as well as in theory (Contreras & Plant, 2006; Craeye, 1998; Sobieski et al., 2009; Wetzel, 1990). Rain causes additional surface roughness, such as crown, stalk, and ring-wave, and all of which will cause increase in emissivity and must be accounted for.

The objective of this study is to assess the impact of rain on L-band measurements. Section 2 briefly summarizes the data used in this study. Sections 3 and 4 characterize the signals under rain for L-band radar and radiometer and develop a rain impact scheme on GMFs. A summary will be given in Section 5.

2. Data

The Aquarius instrument contains three antenna beams, operating at incidence angle of approximately 29, 38 and 46° (referred as beam-1, 2 and 3 respectively). Each antenna beam has one radiometer (1.413 GHz), measuring the first three Stokes parameters (I, Q, U) of earth surface microwave radiation, from which the vertically and horizontally polarized brightness temperatures are obtained, i.e. $T_{BV} = (I + Q) / 2$, $T_{BH} = (I - Q) / 2$. The antenna feeds are shared with the scatterometer (1.26 GHz), measuring the normalized radar cross sections ($\boldsymbol{\sigma}_0$) for co- and cross-polarizations. L-band $\boldsymbol{\sigma}_0$ and T_B measurements used in this study are the version 2.0 Aquarius Level 2 (L2) data, processed with post-launch calibration schemes implemented, including, e.g. radio frequency interference (RFI) filtering, pointing angle correction, drift correction, Faraday rotation correction, etc., as described in the Aquarius Algorithm Theoretical Basis Documents (ATBD) for radiometer (Wentz & Le Vine, 2012) and scatterometer (Yueh, Fore, et al., 2012) respectively. Aquarius Level 2 data is available at the Physical Oceanography Distributed Active Archive Center (PODAAC) at the Jet Propulsion Laboratory (JPL).

To assess the response of L-band $\boldsymbol{\sigma}_0$ and T_B to ocean surface wind and rain, we use ancillary data for wind, wave, SSS, SST and rain, collocated with Aquarius measurements. The ancillary rain matchups were based on Special Sensor Microwave Imager/Sounder (SSMI/S) F17 (Wentz, 1997; Wentz & Spencer, 1998), and WindSAT, a polarimetric microwave radiometer developed by the Naval Research Laboratory Remote Sensing Division and the Naval Center for Space Technology for the U.S. Navy and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) (Gaiser et al., 2004), both with local overpassing time (~5:40 pm for SSMI/SF17 and 6 pm for WindSAT,) close to Aquarius (6 pm). The rain rates were extracted from the version-7 SSMI/S and WindSAT data sets produced at Remote Sensing System, available from www.ssmi.com. We average all SSMI/S and WindSAT data within 12.5 km radius and 1 h time window of the Aquarius footprint for each Aquarius data block. The matchup of NCEP wind speed and direction is routinely performed by the Aquarius Data Processing System (ADPS). The NCEP winds are reported every 6 h on 1° latitude and longitude grid, and are linearly interpolated in time and bilinearly interpolated in space to match up with the Aquarius observations. In addition to the NCEP winds, ADPS has been matching up the Reynolds SST (Reynolds et al., 2007) and Hybrid Coordinate Ocean Model (HYCOM) SSS (Chassignet et al., 2009), which along with the NCEP wind matchups are available in the Aquarius L2 files.

3. L-band radar backscatter under rain

Precipitation mainly affects scatterometer measurements in three ways: (1) the rain column attenuates both the transmitted radar signal and the backscattered signal from the surface; (2) the raindrop itself contribute to signal via volume scattering; (3) rain splash roughens the ocean surface, imposing some modulation on the backscatter cross section (Stiles & Yueh, 2002). The rain impact on the QuikSCAT Ku-band (~13 GHz) measurements has been widely studied to improve the scatterometer vector wind retrieval under rain (e.g. Draper & Long, 2004; Stiles & Yueh, 2002; Weissman et al., 2002). Here, we examine the signature of L-band scatterometer data under rainy conditions.

To generate the rain-free GMF, we perform bin-averaging of Aquarius measured backscatter $\sigma_{0,p}$, (p stands for various combinations of transmitted/received polarization VV, HH or VH), as a function of ancillary wind speed, w (with bin size 1 m s^{-1}) and wind direction, ϕ (at bin size 10°) relative to azimuth angle of radiometer look direction. From these tables, we compute $A_{0,p}$, $A_{1,p}$, and $A_{1,p}$ as a function of w, where,

$$\sigma_{0,p}^{norain}(w,\phi) = A_{0,p}(w)\Big[1 + A_{1,p}(w)\cos\phi + A_{2,p}(w)\cos 2\phi\Big]. \tag{1}$$

The characteristics of the model coefficients are described in Yueh, Tang, et al. (in press). To summarize, A_0 increases with wind speed and decreases with incidence angle, where A_0 for VV is larger than HH. The value for $A_{1,}$ characterizing the up-wind/down-wind difference, has large contrast between different polarizations, with the A_1 values for HH almost double that for VV; while the upwind-crosswind difference (A_2) is very similar between VV and HH.

To assess the effect of rain, we further stratify $\sigma_{0,p}$ into various rain-rate ranges and examine its dependence on w and ϕ under rainy conditions. The bin-average of $\sigma_{0,p}$ is performed in linear units before converted to log units (dB) as shown in Fig. 1, for a few typical wind speeds. It is observed that the signal is very sensitive to rain at low wind speed (0–5 m s^{-1}); even very light rain can cause backscatter to jump up from the rain-free model prediction. There is hardly any resolvable azimuthal dependence at low wind speed, regardless of rain. At medium to high wind speeds (>5 m s^{-1}), the wind direction modulation on the backscatter as predicted by the rain- free model (Eq. 1) is well preserved under rainy conditions, including the transition in asymmetry: from peaking at cross-wind at medium (~5 m s^{-1}) wind to peaking at up-wind/down-wind at high wind speed (>5 m s^{-1}). It is noted that around 5 m s^{-1}, the peak-to-peak difference under rain free condition is reduced under rain.

Using data allocated in each 1 mm h^{-1} rain rate bin, we derived the A_0, A_1 and A_2 coefficients as function of wind speed and rain rate, fitting a second order cosine function similar to Eq. (1). The result (Fig. 2) reveals that, the most dramatic rain induced change is in A_0, particularly at low wind speed (0-5 m s^{-1}), where $A_{0,p}(w,R > 0)$ more than doubled, as compared to $A_{0,p}(w,R = 0)$ at zero wind speed across all rain rates, suggesting that the rain impact is dominated by surface splashing for low wind. The difference between $A_{0,p}(w,R)$ and rain-free $A_{0,p}(w)$ decreases from medium to high wind (5-15 m s^{-1}), where rain splashing effect is probably overshadowed by the roughness generated by the wind.

In the high wind regime (>15 m s^{-1}), $A_{0,p}(w,R)$ is very noisy due to limited sampling, but seems to show a tendency of less scattering for rain rates exceeding 2-3 mm h^{-1}. It is noted that although $A_{1,p}(w,R > 0)$ & $A_{2,p}(w,R > 0)$ are also noisy, they appear to fluctuate

Fig. 1. Aquarius radar σ_{VV} (a) and σ_{HH} (b) for rain rate R = 0 mm h^{-1}(no rain) (black diamond), 0 < R < = 2 mm h^{-1}(red), 2 < R < = 5 mm h^{-1}(green), and R > 5 mm h^{-1} (blue) at selected wind speeds of 2, 5, 10 and 15 m s^{-1} (from top to bottom). Black curves are second order cosine fit for R = 0. Beams1, 2, & 3 are plotted from left to right in each panel.